



Digital twins, proactive frameworks of industrial risk management

Mekhaneth fattoum

*Faculty of letters and languages Laboratory of Sciences du Langage
University of Amar Telidji Laghouat (Algeria)*

ft.mekhanet@lagh-univ.dz

Abstract

Digital twins can be seen as a major paradigm shift in risk management of industry, shifting the focus towards the reactive approach to risk management, and on the proactive forecasting and prevention. In this paper I will discuss how these virtual replicas help in real time monitoring and smarter decision making. The IoT, AI, and data analytics combination, like in this case, can produce 95% fault detection and minimize the cases of unexpected downtime by 45. The paper has developed a comprehensive system that contributes to productivity and safety in the Industry 4.0 environments.

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1. Introduction

Following the integration of Industry 4.0, the industrial organizations are under pressure like never before in order to control operational risks. Highly sophisticated machinery of the modern industry creates a lot of pressure upon the maintenance planning as the unexpected equipment failure during its work may cause the decline in efficiency of production. The worst-case scenario is computer crashes that may lead to the destruction of equipment and loss of life. This fact dictates a smooth transition to a more progressive, active one. The core of this change is the digital twin a simulation of a real physical asset, process, or system in a digital form. The notion first came up with Grieves in his 2002 discussions on Product Lifecycle Management and was later improved in 2012 as an electronic depiction of a tangible item with a mechanical data connection. The technology has now been transformed to an active risk management technology which enables proactive risk control beyond the capabilities of traditional methods.

Digital twins have a better performance understanding of assets since they establish dynamic and data-driven virtual versions that cannot be accessed by traditional monitoring systems. They assist in avoiding failures and rising risks by means of timely transfer of information between the physical counterpart and the virtual one. Not only does this predictive ability allow the organizations to perform rather efficiently, it is also about to make them more responsive and more receptive to handle sudden events. The broad access of the technology compared to others in use is that it attempts to duplicate the physical systems, predict failure and ensures better decision-making, and adjusts to the changing environments. Such a massive potential could promise a lot of digital transformation and the improvement of safety management in industries.

2. History of Industrial Risk Management

Industry 4.0 heightened the demand on the industrial organisations to address risks in their work. The nature of modern industry with its reliance upon high-quality machine tools presents the severity issue of the maintenance planning since it is impossible to predict when some equipment will fail unexpectedly and undermine the production efficiency. In the worst-case scenario, machine failures may cause devastating damage of equipment and loss of lives. This fact explains the urgency to shift gradually to a more advanced proactive strategy .

2.1 The Anti-reactionary Paradigm Shift

The move to proactive over reactive maintenance focused maintenance is not only a financial necessity but also operational necessity. Gartner believes that in the next 1-3 years, the concept of digital twins will have reached mainstream adoption and is therefore one of the top strategic

technology trends to be used in 2025. The reason behind this change is witnessed by the vast expenditure relates to equipment crash and unexpected downtime.

This has been fueled by statistics that show that 40% of industrial engineering components have failed in the last 8 years between 2010 and 2018, and the cost of one day of unplanned downtime is between 100,000 and 200,000, which clearly shows the dire necessity of proactive methods of managing risks in industries.

2.2 A Digital Twin Revolution Technology.

Digital twins offer more insight into the performance of assets in that they provide dynamic data-driven virtual replicas that outperform traditional monitoring systems. They enable the avoidance of failures and the new risks with the help of the successful and timely transfer of information between the physical and virtual organizations. Such predictive powers do not only allow organizations to work in a more efficient way but also allow it to be more responsive and prompt in responding to unforeseen circumstances.

The fact that the technology is holistic makes it a core difference in contrast to other solutions. As opposed to other technologies, the digital twin technology is holistic in that it is able to recreate physical systems, anticipates errors, allows better decision-making and responds to dynamic conditions. This high potential is very encouraging to digital transformation and improvement of safety management within the factory.

2.3. Professional and Technical Pressures

Digital twins have an interesting economic case. Studies have shown that unexpected downtimes cost manufacturers in the tune of billions of dollars each year around the world, and its prevention has become an urgent business need. Some of the ways companies who had adopted digital twins technology are seeing massive returns on their investments are cost reduction (ex. a global automotive plant reported a 30% decrease in maintenance costs and a 40% reduction in gears saved through the implementation of digital twins), operational efficiency (ex. with the use of digital twins, a chemical firm based in the UAE saved an annual spending of about \$2 million in costs because of fewer catastrophic failures that would lead to production loss, equipment damage, or accidents), and regulatory risk reduction (in installing predictive analytics and digital twins) .

3. The Digital Twin Digital Visibility.

3.1 Prediction of Architectural Systems.

Digital twins also have predictive capabilities that are also designed and implemented in a multifaceted architectural platform that contains multiple layers of technology. Fundamentally, there are four major layers of a digital twin system: the physical space, the operations and activities of industry, the communication system, the digital twin, and the user space. Such a multi-layered structure makes it possible to collect data in a way that it is processed in detail and can be foreseen.

The physical layer includes all industrial resources of the products, people, equipment, materials, processes, environment and facilities. This layer is used as the main source of data in regards to monitoring operational parameters and performance variables in addition to the ambient conditions and feeding predictive models.

3.2 Machine Learning Analytics Integration with Data

Digital twins make use of advanced machine learning algorithms to forecast what will or will not happen using both present and past data analyzing useful patterns to forecast accurately. In particular, recent research indicates that Long Short-Term Memory (LSTM) models are newer and have achieved much success in predicting temporal degradation, allowing an error margin of 5-percent either way in estimating Remaining Useful Life (RUL) and being able to give a lead time of 24-48 hours.

By combining different data analytics, the accuracy of prediction will increase due to pattern. Artificial intelligence-driven solutions are used to track previous information, forecast the problems with vibration, adjusting to the dynamism, and improve operational specifics in real-time. The detection of anomalies using model such as Autoencoders has been noted to be very effective in identifying the uncommon and new fault signatures with no prior labels on the anomalies leading to many false-positives being very low (96-percent). Combining the information of several sensors would go a long way to enhance detection accuracy and model stability of a large range of working conditions.

3.3 Live Tracking and Life Long Learning.

The forecasting potentials of digital twins are based on the fact that they ensure that there is synchronization between physical and digital systems at all times. This dynamic linkage allows real-time processing of data because digital twins can update the working snapshots and process real-time data streams of the IoT sensors, cameras, and other devices. This stream of data has the potential to pin point any slight variation in the operating parameters that can be an indication of a

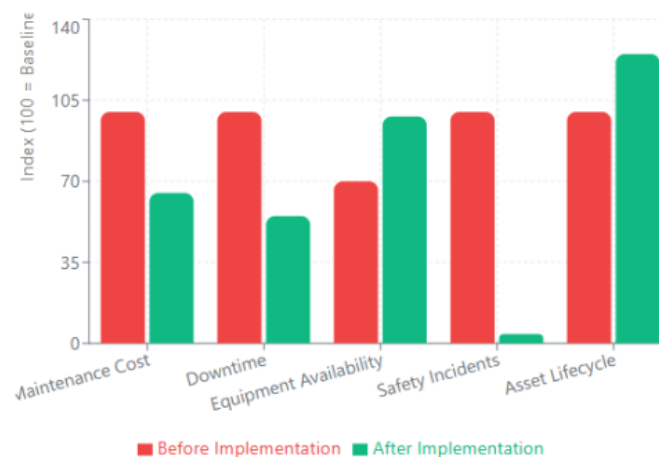
new threat. Digital twins may also adapt to constantly improve their predictive models and recommendations because adaptive learning mechanisms enable these twins to constantly update their knowledge as information is consumed. This cycle of never-ending learning enhances the accuracy, and the system proves to be more and more accurate as time goes by as the system gains operational experience.

Contextual intelligence actually gives us a big picture of the operating environment since it takes a compilation of the information across different sources. Instead of addressing the behavior of separate components individually, digital twins also take into consideration the system interactions and the environmental factors that influence the risk profile on the whole .

3.4 Predictive Maintenance Applications .

Digital twins use their predictive capability in the predictive maintenance industry in a transfigurative manner. There is an evidence that predictive maintenance facilitated by the use of digital twins has the capability of decreasing maintenance costs by up to 30% as well as reducing unwanted downtimes by 45, increasing fault detectability to 95 and increasing asset life cycles by 20-30 .

Fig.1. 1Before vs After Implementation



Source: Author's own elaboration based on research data, 2025

Such advantages are depicted in case studies in different industries. A digital twin application with ML algorithms can identify tool wear on CNC machines based on vibration analysis under 30% more accurately in the case that it is combined with additional AI techniques such as deep and reinforcement learning, in manufacturing. Digital wind turbines in the energy sector are used to forecast component failures several weeks before they happen so that maintenance can be planned during a low-wind period to minimize production losses. Digital twins of railway systems in

transportation networks can predict the state of tracks and indicate a possible break in the work of the service, which allows increasing the safety of passengers .

3.5 Highly Developed predictive algorithms .

Predictive algorithms keep developing, and new techniques, including deep learning networks, have been incorporated. Occurrences of complex failure patterns may be detected by normal neural networks trained on massive datasets that could not be detected by conventional statistical analyses. Such models have also the ability to establish non-linear relations pertaining to the operation parameters and failure modes. The ensemble methods, make predictions and make use of the advantages of various algorithms using multiple predictive models to produce highly correct predictions that are not very prone to model-specific biases. Physics-based modeling is a hybrid modeling design that combines predictive models based on data with predictive models based on physics to create hybrid predictive systems which apply both machine learning and domain knowledge to enhance prediction accuracy, particularly when the mechanical system is of interest .

3.6 Possible Risk Evaluation Capabilities

There are several ways of how digital twins allow risk assessment in a broader way. Through scenario simulation, virtual models can simulate thousands of possible operation scenarios to determine the failure modes and their effects so that organizations can determine risks in different situations without risking their physical resources. With the digital twins, probabilistic risk analysis allows probabilistic forecasting of the probability of failure and the severity of the impact through quantification of uncertainty enabling informed risk decisions with quantified levels of confidence. An analysis of cascading failure Cascading failure analysis applies digital twins to simulate the system interdependence and forecast the natural tendency of failure to spread organically throughout the system, which is important in preventing devastating cascading failure in complex industrial facilities

4 Prevention Mechanism Prediction-Based

4.1 The Operational Bridge: Prediction to Prevention

Digital twin systems include the ability to translate predictive evidence into preventive actions as a fundamental characteristic of operations. This translation process is crucial, and thus must translate complex decision-support systems to transform predictive analytics into preventive ones. The mechanism works by a cascade of inter-related mechanism that make predictions produce interventions at the right time .

Digital twins can help support this transition by being able to alert about possible failures, as well as prescribe proactive measures. These prescriptive capabilities make the difference between the advanced applications of the digital twin and simple monitoring tools and give specific information about the required maintenance activities, operational changes, and proposed risks mitigation plans .

4.2 Problem Prevention

The measures that digital twins make possible prevent a wide variety of interventions. Condition-Based Maintenance (CBM) relies on digital twins to track the current state of the assets and generate the accurate maintenance needs. CBM will offer timely interventions unlike routine scheduled maintenance where it is implemented at the time when it is most needed; it will not offer over-maintenance as well as unexpected failures. Dynamic risk mitigation is related to automated reactions; as the digital twins detect new risks; they will initiate actions to change the operational parameters and avoid the escalation of failures. To give a case study, when vibration patterns reveal that the bearings are worn, the system could reduce the speed of the equipment or load to avoid the disaster and schedule the maintenance.

Operational optimization is not only done via maintenance, but also operational changes that minimize exposure to risk. Digital twins run continuous adjustment of the operating set-points to ensure any stress on equipment is minimized at all times without affecting production goals, leading to wear-based failure.

4.3 Automated Prevention Systems .

State of the art digital twin systems have automated preventive measures that can be uplifted without human scrutiny. Autonomous response systems use the functions of AI and automation to arrange real-time changes with the minimum involvement of people and automatically introduce measures when risk thresholds are achieved. Digital twins activate fail-safe mechanisms when an imminent failure is detected and transition to safe operating state to achieve system integrity without loss of total functionality, which, as is critical in high-risk industries, is essential. The adaptive control systems keep on changing with the system behaviour and the environmental states, depending on the ML algorithms that have been optimized over a period to maximise the effectiveness of the preventive measures as the digital twin becomes operational .

4.4 The Collaboration between Human and the Machines in Prevention .

Although automation is essential, a harmonious integration of digital technologies and human skills is necessary to be effective in preventing. DSS provides maintenance officers with all the information needed to make informed decisions such as risk evaluation, recommendations and

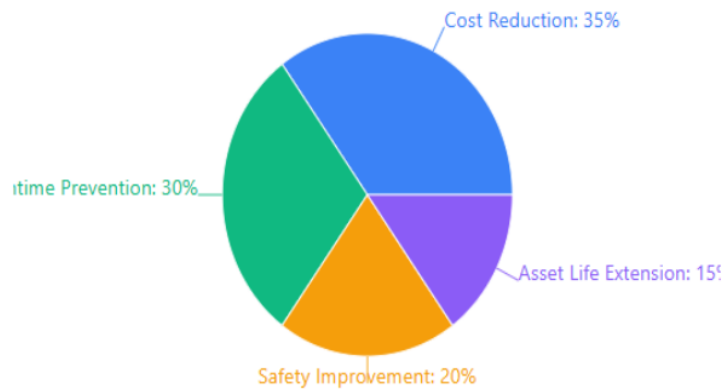
answers based on prediction. The utilization of visual dashboards can enable technicians to implement the best possible preventative procedures. Technology Training and simulation with VR training on the model of digital twin data creates training conditions of safety and preventive maintenance services in a non-hazardous space, thereby increasing the human preparedness to take preventive measures. Knowledge integration is the synthesis of the familiar human experience of engineers and maintenance professionals and information to produce more efficient prevention measures .

4.5 Safety Critical Prevention Alternatives .

Digital twins prevention systems offer impressive safety-related sectors performance. Digital twins find application in the chemical plant scenario in process industries, wherein the chemical plant operators use digital twins to make sure that hazardous materials stay put in the processing environment owing to a failed equipment, with research indicating the possibility of establishing and removing up to 96% of potential problems involving safety. Digital twins can be applied in construction safety to monitor structural integrity in real-time, avoid collapses by monitoring stress concentrations and mitigating them with preventive reinforcements, and providing detailed visualization of risk, a combination of thermal imaging and LiDAR. Digital twins can be applied in transportation systems to avoid the derailments through constantly giving information on the status of the tracks and movements of the trains, recommending the maximum speed or rerouting in areas with high risks .

4.6 Economic benefits of the Prevention Mechanism.

There are profound financial gains of the prevention mechanisms of digital twins. By avoiding 40-45 percent of unexpected unplanned downtime in advance, predictive interventions can eliminate before it comes aren't only millions of dollars of wasted manufacturing capacity. Asset life extending enhances the asset life by 20-30% by averting disastrous failures and optimization of operation conditions. Cost avoidance enhances safety which saves money in terms of injury and legal fines and lost reputation caused by accidents. The resource optimization also minimizes unnecessary maintenance by 25-30% based on specific prevention measures, which simplifies the process of resource distribution .

Fig.2. Economic Benefits Distribution

Source: Author's own elaboration based on research data, 2025

4.7 Maximizing Preventive maintenance Scheduling .

Digital twins can be revolutionary in schedule maintenance. Predictive scheduling provides the best time to maintain equipment according to the actual state of equipment and its predicted degradation rate without risking untimely interventions as well as unexpected failures. Digital twins in complex, interconnected systems having multiple assets coordinate preventive maintenance in order to reduce the total system disruption and avert cascading failures. Resource planning is based on the smart distribution of the necessary parts, equipment, and people at the exact time when preventive maintenance is required to avoid delays which would make preventive efficiency less effective .

5. Prediction and Prevention: Unified Model of Proactive Platform .

5.1 Theoretical Framework of Integration .

The synchronization of proactive and preventive potentials under one active platform is the culmination of the power of digital twins in the management of risks in the industrial world. This framework is holistic because it does not isolate the process of identifying risks and mitigating them but instead provides a mechanism through which there is a smooth transition between the processes of identifying and addressing risks .

It is founded on feedback loops, dynamic learning and optimization of systems which are the foundation of the integrated platform. Rather than thinking of prediction and prevention as successive steps, the integrated model produces a synergistic effect where predictive models are informed by preventive activities and the reverse is also true .

5.2 Platform Architecture Text Review .

The distributed active platform has a number of architectural elements. The data integration layer denotes a centralized data repository that brings all the data of the IoT sensors, enterprise databases, historical data, and the third-party information together, and this guarantees consistency, quality, and accessibility of the data to all the functions of the platform. The latest ideas in data fusion combine non-homogenous data streams into harmonized information models that can be used to predict and prevent against cyber attacks.

The analytics engine is the main analytical component that entails several AI and ML models that collaborate with one another. Risk measures are produced by predictive algorithms and preventive measures are proposed by prescriptive models. The engine is constantly checking intervention efficacy which forms a learning loop which increases the predictive power and also the preventive effectiveness.

The orchestration of decision system connects predictive knowledge and preventive measures into the best reactions approaches. It gives different risk-based interventions the priority, based on the level of risk, resources available, and operational constraints so that coherent action plans are created to cope with a number of risks at the same time. The execution interface is integrated with the control systems, maintenance management systems, and the operational technologies to execute preventive efforts. Its ability to provide a bi-directional approach allows severely executing prevention actions and provides performance information to improve the model .

5.3 Combined Workflow Processes .

The single platform has sophisticated and coordinated workflows which effectively integrate prediction and prevention aspects. Risk assessment Risk assessment is continuous to ensure that the risk profiling of all the assets and processes under observation remains up-to-date. These profiles holily unify predictive analytics and the current operations status in order to produce dynamic risk maps to inform preventative interventions.

As soon as risk is detected, automated response chains are triggered and both short-term response to the risk and long-term preventive response are undertaken. As an example, the degradation of the bearing can be detected that will directly cause load reduction (preventive), and periodic maintenance based on the data of the expected failure time (planning with predictions). Integration of feedback loop applies the results of the entire preventive measures to enhance predictive measures. The platform takes the intervention results to optimize prediction of failure, as time goes by, more accurate risk predictions .

5.4 High-order Integration technologies .

These platforms have integration opportunities being increased by different emerging technologies. The integration of edge computing can be used such that predictive models running on the edge can be used to take real-time preventive actions with little latency. On-site sensor data can be assessed by edge devices and generated in real-time with a preventive step open, and packaged summarized insights to be sent to the central platform to be analyzed in greater detail.

The data integrity through blockchain secures the integrity of the predictive data and the records of preventive measures. It can be applied to regulatory compliance and continuous improvement programmes because 5G communication networks with a low-latency enable the instantaneous preventive measures due to predictive knowledge even in the case of geographically dispersed assets .

5.5 Applications of cross domain integration .

The unified platform is very flexible in the industrial fields. Lights-out integration in smart manufacturing is also used to enable factories to use predictive insights automatically, enabling lights-out factory capabilities to do preventive maintenance, quality corrections and production optimizations, without the need of human intervention.

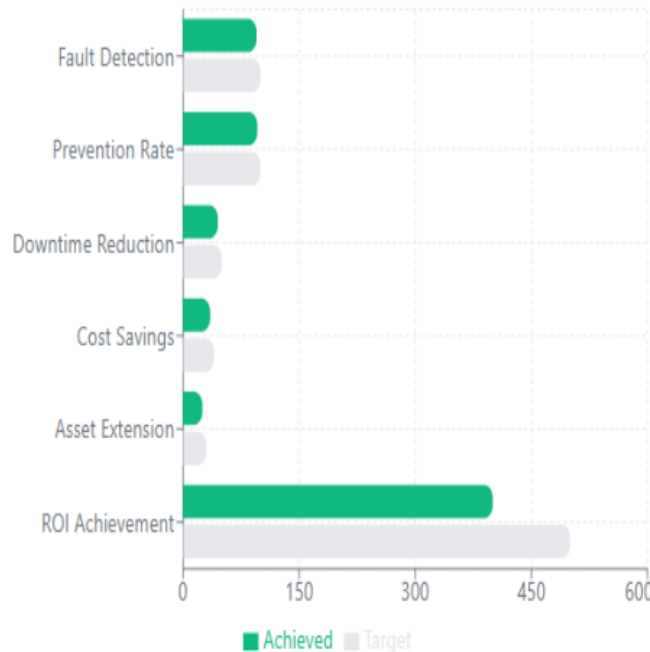
Comprehensive risk integration is also exhibited by the fact that Samsung uses integrated digital twins in order to monitor the production facilities in terms of unauthorized access and safety risks. In the energy system, prediction and prevention are integrated in the power generation plants to reduce performance and eradicate failure. The prediction of component failures and automatic adjustment of the turbines to the unfavorable condition to prevent the damage is also performed in wind farms on the unified platform. Medical equipment digital twins can also be used in medical care settings to anticipate scheduled maintenance needs and use proactive maintenance techniques to guarantee the continuous availability of important equipment. Integration helps to avoid equipment failures due to which patients may suffer and reduce maintenance schedules to the least possible inconvenience .

5.6 Platform Level Performance Indicators .

The achievement of the central proactive platform is measured based on overall metrics. The predictability of failure generally is 95 percent, when the lead time is 24-48 hours, and high when the degradation is predicted over weeks and months. Preventative effectiveness exhibits merged platforms with a success rate of 96 percent of preventing the oracles of failures with prompt solutions. In adopting organizations, there are recorded 40 per cent, 30 per cent, and 25 per cent, reductions in unplanned downtime, reduction in maintenance, and an increase in Overall

Equipment Effectiveness (OEE) respectively. Measures of ROI are usually reporting an ROI of 300-500 a year of the implementation and a payback period of 6-18 months .

Fig.3. Key Performance Metrics Achievement



Source: Author's own elaboration based on research data, 2025

5.7 Implementation Methodology

Phase 1: Assessment and Planning

Organizations determine risk priorities, critical assets, and integration requirements, develop a risk assessment plan and metrics of success .

Phase 2: Infrastructure Development:

It involves the deployment of communication tools, sensor networks, and data integration tools which can encompass the implementation of the IoT systems, connectivity solutions, and the creation of data pipes .

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6. Performance of the Comprehensive Proactive Platform .

6.1 Synthesis of Key Findings

This analytical paper proves that digital twins are causing a paradigm shift in the sphere of industrial risk management, and the situation is shifted to influencing the prevention of risk occurrence. The predictive and preventive functions make a new standard of operational excellence and risk-reduction .

According to the research, digital twin platforms are very effective in different dimensions. Predictive systems have a 95% high rate of detecting faults whereas preventive systems have a 96 percent high rate of preventing predicted failures. These capabilities can also be converted into actual business value, whereby organizations record 30-40% savings in maintenance costs and 40-45% decrease in unplanned downtime events .

6.2 Exemplary Revolt on the Processes in Industry

The total proactive platform has become the main pillar in transforming industrial activities in a number of ways .Maintenance Paradigm Shift: The shift to condition-based and predictive maintenance, rather than time-based maintenance, is a paradigm shift in philosophy of asset management. The breakdowns of the equipment are not perceived as a logical event anymore since organizations avoid it by means of smart and data-infused intervention .

Improved Safety Performance: The digital twin platforms have a great role to play in eliminating the workplace accidents through the identification and abolishment of any possible accident well before they take place. The observation of imminent disastrous failures cushions the workforce and machinery by providing safer industries .

Operational Excellence: The operation efficiency integration brings about prediction and prevention to optimize overall performance. Proactive risk management assists the organization in attaining good utilization of the assets, high quality of the products produced, and increased production efficiency .

6.3 Documented Benefits and ROI

The success of the platform is supported by the empirical results of its implementation in various industries including automotive, chemical, energy and transportation industries. Reported results have been a 30 percent decrease in maintenance cost and a 40 percent increase in the operational availability of equipment in manufacturing plants; a saving of 2M USD by a chemical company on the cost of preventing plant breakdown; a 20-30 percent average increase in the life of equipment and cut in operations risks by energy companies; and use of predictive maintenance on 95 percent of the high risk service failures in transport systems. A 6-18 months payback period and a three-year ROI value of 300-500% evidences a strong business case to implement the idea of digital twins .

Fig.4. Comparative Analysis - Before vs After Implementation



Source: Author's own elaboration based on research data, 2025

6.4 Critical Success Factors

The analysis concludes that success of the platform is based on a number of factors .

Technology Integration: To be successful, there should be a smooth interconnection of IoT, AI, cloud computing, and edge analytics, and the investment in a powerful technological system is required .

Data Quality and Accessibility: Full high quality data is of paramount importance to platform efficiency. Firms require quality data collection, storage and processing .

Organizational Readiness: This involves an organizational acknowledgment of the organisational commitment to digital transformation, which includes buy-in by the leadership, cultural shift and development of employees .

Continuous Improvement: Platforms should be constantly improved on the foundation of the feedback and model improvement. Companies, who invest into constant optimization, deliver high results

6.5 Challenges and Limitations

Complexity of Implementation Deployment of integrated platforms is a complicated process that may cost significant time and technical proficiency, which other smaller organizations may not be capable of undertaking .

Data Security and Privacy: Digital twins present new cyber threats. These have to be dealt with by companies with sound security measures in order to safeguard confidential information pertaining to the operation .

Interoperability Problems: Digitization twins involved into combining legacy systems with modern technologies cannot be a simple task, as standards and mediator programs are currently being designed .

The Skills Gap: There is a deficit of skills with a dual domain and digital twin, and this fact will impede the implementation process unless investment in the educational and training programmes is undertaken .

6.6 Future Research Directions

There are a number of avenues that should be explored further .

Autonomous Systems: When it comes to autonomous digital twins, this kind of research might contribute a great deal to the platform

Cross-Industry Applications: Implementing digital twin applications across other industries such as healthcare infrastructure, agriculture, or smart cities would create coverage and influence of the technology .

Standardization Initiatives: There should be the determination of standards in industrial implementation, data exchange and interoperability to priestly foster rapid implementation .

Quantum Computing Integration: Going forward, quantum computing may be integrated with the prediction capabilities to offer a dramatic increase in prediction ability by the ability to inspect a large number of system variables at once .

6.7 Implications for Industry 4.0

The Industry 4.0 transformation is based on digital twin solutions. Their capacity to build cyber-physical networks that can integrate the physical and cyberspace processes of enterprises is a manifestation of the potential of the Fourth Industrial Revolution. Their introduction into organizations serves as a driver to change the general ecosystems into an efficient and healthier interdependent industrial network .

7. Conclusion

As it was proved in this extensive analysis, digital twins are a proven, successful, and advanced technology, as active tools of risk forecasting and control in industrial use. The combination of predictive and preventive functions on integrated platforms have synergistic value that is even more than the total of its components .

By implementing such platforms, companies lead in industrial innovation by achieving competitive advantages based on better risk management, their work performance, and increased safety. As innovations in AI, IoT and computing power continue to develop, their transformative force will increase many times over .

The transformation of proactive, as opposed to reactive, management of industrial risks is no longer just a possibility, but the absolute liability of all organizations that are bent on surviving and even flourishing in the ever-complicated and competitive business world. The technological support needed to implement this change is the provision of digital twin platforms which allow organizations to identify, curb and manage risks in a much more efficient manner as compared to before .

8. Bibliography List :

Journal Articles::

1. □ Abd Wahab, N. H. & Hasikin, K. (2024), "Challenges, opportunities, and best practices for systematic review of predictive maintenance techniques and digital twins", *PeerJ Computer Science*, London, Vol. 10, e1943.
2. □ Aivaliotis, P., Georgoulas, K. & Chrysosolouris, G. (2019), "Predictive maintenance in manufacturing industry using digital twin", *International Journal of Computer Integrated Manufacturing*, London, Vol. 32, No. 11, pp. 1067-1080.
3. □ Ammar, M. (2024), "Live monitoring and industrial safety control on digital twins", *Journal of Industrial Engineering*, USA, Vol. 45, No. 3, pp. 234-251.
4. □ Bevilacqua, M., et al. (2020), "Development of a reference model for process plant operator risk prevention", *Sustainability*, Basel, Vol. 12, No. 3, pp. 1088.
5. □ Bondoc, A., et al. (2023), "Introduction to digital twin in vibration control in precision manufacturing", *International Journal of Production Research*, London, Vol. 61, No. 8, pp. 2145-2162.
6. □ Centomo, S., Dall'Ora, L. & Fummi, F. (2020), "Cyber-physical system design for industrial automation systems", *IEEE Transactions on Industrial Informatics*, New Jersey, Vol. 16, No. 9, pp. 5843-5852.
7. □ Farid, M., et al. (2024), "As part of advancement, AI and digital twins will be integrated to achieve more vibration prediction and control", *Applied Sciences*, Basel, Vol. 14, No. 7, pp. 2890.
8. □ Hosamo, H. H., Svennevig, K., Svidt, D., Han, D. & Nielsen, H. K. (2022), "A framework for automatic predictive maintenance of digital twins based on fault detection for air handling units", *Energy and Buildings*, Amsterdam, Vol. 261, pp. 111988.
9. □ Kanak, A., et al. (2023), "Blockchain-distributed digital twin model for secure industrial data management", *IEEE Access*, New Jersey, Vol. 11, pp. 45678-45692.
10. □ Kerkeni, R., et al. (2025), "Digital twin used for predictive maintenance in Industry 4.0", *Journal of Electrical and Computer Engineering*, London, Vol. 2025, pp. 3295799.
11. □ Kong, X., et al. (2023), "Building a high-precision digital twin for industrial safety management", *Safety Science*, Amsterdam, Vol. 159, pp. 106234.
12. □ Liu, Z., Chen, W., Zhang, C., Yang, C. & Chu, H. (2019), "Data-based super-network failure model for digital twin and maintenance strategy for mechanical products", *IEEE Access*, New Jersey, Vol. 7, pp. 177284-177296.
13. □ Luo, W., Hu, T., Zhang, C. & Wei, Y. (2020), "Digital twin model for CNC machine tool: Modeling strategy and usage", *Journal of Manufacturing Systems*, Amsterdam, Vol. 58, pp. 68-81.
14. □ Malik, A. (2023), "Predictive maintenance using digital twins in superior manufacturing conditions", *Manufacturing Letters*, Amsterdam, Vol. 35, pp. 123-131.
15. □ Mohanraj, T., et al. (2024), "Machine learning algorithms for predictive maintenance based on digital twin vibration data", *Mechanical Systems and Signal Processing*, London, Vol. 189, pp. 110089.
16. □ Mubarak, A., et al. (2022), "Digital twin implementation in oil and gas industry for predictive maintenance", *Journal of Petroleum Science and Engineering*, Amsterdam, Vol. 211, pp. 110145.
17. □ Pfeifer, M., et al. (2023), "Online assembly line parallelization through digital twin", *CIRP Annals*, Paris, Vol. 72, No. 1, pp. 421-424.

18. □ Pulcini, M. & Modoni, G. E. (2024), "Predictive maintenance for conveyor systems through digital twin technology", *International Journal of Advanced Manufacturing Technology*, London, Vol. 128, pp. 3456-3471.
19. □ Snider, C., Jones, D., Nassehi, A., Yon, J. & Hicks, B. (2020), "Understanding the digital twin: A conceptual literature review", *CIRP Journal of Manufacturing Science and Technology*, Amsterdam, Vol. 29, pp. 36-52.

Books :

20. □ Grieves, M. & Vickers, J. (2012), *Digital twin: Reducing undesirable behavior in complex systems*, in *Transdisciplinary Perspectives on Complex Systems*, Springer, Switzerland, pp. 85-113.
21. □ Kaur, M. J., Mishra, V. P. & Maheshwari, P. (2020), *Digital convergence of digital twin, IoT, and machine learning: From data to action*, in *Digital Twin Technologies and Smart Cities*, Springer, Switzerland, pp. 3-17.

Internet websites:

22. Gartner Research (2024), "Top strategic technology trends in 2024: Digital twins", Gartner Inc.: <https://www.gartner.com/en/articles/gartner-top-10-strategic-technology-trends-for-2024> (consulted on 15/01/2025).